RM No. E8C0[illegible]

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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF COMBUSTION IN FLOWING GAS WITH VARIOUS TURBULENCE PROMOTERS

By Gordon W. Haddock and J. Howard Childs

Flight Propulsion Research Laboratory
Cleveland, Ohio

TECHNICAL EDITING WAIVED

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
WASHINGTON
June 7, 1948

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PRELIMINARY INVESTIGATION OF COMBUSTION IN FLOWING GAS WITH VARIOUS TURBULENCE PROMOTERS

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SUMMARY

An investigation was made of combustion occurring downstream of various turbulence promoters in a 20-inch length of $1\frac{7}{8}$-inch inside-diameter, water-jacketed tubing using premixed vaporized fuel and air. Metered quantities of water were injected to reduce the outlet temperatures to values that could be measured with thermocouples and a heat balance was made to determine combustion efficiencies. The nominal length available for combustion was altered by changing the position of a movable water spray.

Among the turbulence promoters investigated were flat plates perforated with 1/8-inch diameter holes, 1/4-inch diameter holes, and a single large hole to give 12.4, 17.2, and 21.5 percent open area, respectively. For each percentage of open area investigated, the turbulence promoter with the intermediate (1/4 in.) hole size gave stable combustion at the highest inlet-air velocity. The turbulence promoters with the largest percentage open area (21.5) gave stable combustion at the highest inlet-air velocities for a fixed inlet-air pressure, probably because the pressure in the combustion zone increased with increased open area.

At an inlet-air temperature of 80° to 90° F and an inlet-air pressure of 39.7 pounds per square inch absolute, combustion could not be maintained with any of the turbulence promoters investigated at fuel-air ratios below 0.05 or at inlet-air velocities above 87 feet per second. At the higher inlet-air temperature investigated (200° or 225° F), the limits of combustion were somewhat wider. Combustion efficiencies ranged from 85 to 95 percent for all conditions investigated. The ratio of the isothermal total-pressure loss to the inlet-air velocity pressure computed from the upstream density and the cross-sectional area of the combustion zone was approximately the same as values computed for the primary combustion zone of a typical gas-turbine combustor. Flame lengths of about 2 inches were indicated.

INTRODUCTION

The combustion process in gas-turbine and ram-jet engines takes place in a steady-flow, turbulent air stream into which fuel has been injected. In order to investigate the role of turbulence in this process, the effect of turbulence must be isolated from the effects of the other variables, such as pressure, temperature, velocity, fuel-air ratio, air distribution, and fuel atomization and distribution, which are known to influence the combustion process (reference 1 and NACA unpublished data).

The apparatus and the preliminary results from an investigation conducted at the NACA Cleveland laboratory on the effect of several turbulence promoters on continuous combustion in a flowing gas are described. The turbulence promoters were investigated at controlled steady-flow conditions of pressure, temperature, velocity, and fuel-air ratio in a homogeneous mixture of vaporized fuel and air. With each turbulence promoter, data were obtained on ignition characteristics, stability limits of combustion, combustion efficiencies, pressure losses, and nominal flame lengths.

No attempt was made to evaluate the turbulence resulting with each turbulance promoter or to correlate the data as a function of the turbulent conditions.

APPARATUS AND INSTRUMENTATION

A photograph and a diagram of the apparatus are shown in figures 1 and 2, respectively. Air was admitted from the laboratory air supply; an electric heater controlled the inlet-air temperature and a valve controlled the inlet-air pressure and flow. After being heated above its normal boiling range in an auxiliary heat exchanger, AN-F-22 fuel was injected through multiple orifices into the air stream at a point 20 inches upstream of the turbulence promoter. Combustion occurred downstream of the turbulence promoter in a 20-inch length of water-jacketed $1\frac{7}{8}$ inch inside-diameter monel metal tubing. A movable water spray inside the water-jacketed tube made it possible to shorten the nominal length available for combustion to any desired value. Downstream of the water-jacketed tube was a length of 4-inch insulated pipe in which the water vaporized and mixed with the exhaust gases. The exhaust-gas water-vapor mixture was passed to the laboratory exhaust system; a slide valve controlled the exhaust pressure.

The ignition source was a spark plug with extended electrodes passing through a water-cooled passage so as to avoid any hot spots on the flame-tube walls. The spark electrodes were flush with the

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tube walls. The movable water spray consisted of six radial spokes branching at right angles from a central shaft through which the water was supplied. Multiple orifices in each of the radial spokes injected water in a fine spray normal to the flow of gases.

The turbulence promoters were fabricated from 1/16-inch Inconel and were suspended by spot welding from the $1\frac{5}{8}$-inch tube supplying the fuel-air mixture. One turbulence promoter consisted of a 30° cone with 29 holes 1/8 inch in diameter drilled in its surface, as shown in figure 3. The other turbulence promoters (fig. 3) consisted of three series of flat plates with 12.4, 17.2, and 21.5 percent open area. In each series were three individual turbulence promoters having 1/8-inch holes, 1/4-inch holes, and a single large hole. With two of the turbulence promoters having 1/4-inch holes, addition of a single 1/8-inch hole was necessary to obtain the desired percentage of open area. The values of percentage of open area that were investigated correspond to values used in the primary zone of current gas-turbine combustors. Investigation of turbulence promoters giving higher values of percentage of open area (values corresponding to current ram-jet combustors) was impossible because stable combustion could not be maintained with these turbulence promotors.

Water flow to the cooling jacket and to the movable water spray and the fuel flow were measured by calibrated rotameters. Air flow was metered by a sharp-edged orifice with vena-contracta taps installed according to A.S.M.E. specifications. Inlet-air pressure was measured by a calibrated gage and pressures were measured at 1-inch intervals downstream of the turbulence promoter by mercury manometers. The inlet-air temperatures immediately upstream of the fuel injector and the outlet-gas temperatures at the downstream end of the insulated 4-inch pipe were measured by six-point chromel-alumel thermocouple rakes. The fuel temperature at the injector inlet was measured by a single chromel-alumel thermocouple. All thermocouples were connected to a self-balancing, indicating potentiometer. Temperatures of the water at the the inlet to the movable spray and at the inlet and the outlet of the cooling jacket were measured by calibrated mercury thermometers.

PROCEDURE

Ignition was obtained at a pressure above 40 pounds per square inch absolute, an inlet-air velocity of 30 to 40 feet per second, and a fuel-air ratio of 0.065 to 0.080. Following ignition, the operating variables were adjusted to the desired values. The water flow through the cooling jacket was maintained constant throughout the investigations at a value that resulted in a temperature rise in the jacket of about 60° F. The water flow to the movable water spray was adjusted to give an indicated temperature of about 1200° F at the downstream thermocouple rake. The position of the movable spray was fixed 20 inches downstream of the turbulence promoter at all times except when flame lengths were investigated. The fuel temperature at the inlet was maintained approximately constant at 400° F. At the lower inlet-air temperatures, the temperatures of the fuel-air mixture immediately upstream of the turbulence promoter averaged 5° to 10° F above the inlet-air temperature.

In order to determine the stability limits of combustion, all of the operating variables (based on conditions upstream of the turbulence promoter) except one were maintained constant and that one was gradually altered until combustion ceased (blow-out) or became unstable. For example, in order to determine the lean fuel-air-ratio limits, inlet-air pressure, inlet-air temperature, and inlet-air velocity were maintained constant and the fuel flow was gradually decreased until blow-out occurred. The fuel-air ratio at which blow-out occurred was recorded as the lean limit for those particular conditions.

Combustion efficiencies were determined by maintaining all operating variables constant for 5 to 20 minutes until all readings attained their equilibrium values; data were then recorded.

The movable water spray was positioned progressively closer to the turbulence promoter and data were recorded at each position of the spray to determine nominal flame lengths. Nominal flame length was recorded as the distance from the turbulence promoter to the spray when an appreciable drop in combustion efficiency or blow-out occurred.

Data were also obtained on the pressure loss through each turbulence promoter for isothermal (no-burning) conditions and for burning conditions when combustion-efficiency data were also recorded.

Combustion efficiencies were computed as follows: The enthalpy of the combustion gases at the position of the downstream thermocouple rake was obtained from the thermocouple indication (uncorrected for radiation or stagnation effects) and the measured fuel and air flow using the data of references 2 and 3. The enthalpy of the water vapor at this same position was obtained from the thermocouple indications and the measured water flow to the movable spray using the data of reference 4. These values were added to obtain the total enthalpy at the position of the downstream thermocouple rake. This value was corrected for the heat transferred to the cooling jacket and the inlet enthalpies of the air, the fuel, and the spray water were subtracted to give the total rise in sensible enthalpy. The percentage ratio of this enthalpy rise to the net heating value of the fuel was recorded as combustion efficiency.

Inlet-air velocities and velocity pressures were calculated from the inlet-air densities using the cross-sectional area of the $1\frac{5}{8}$-inch inside-diameter tube. The percentage of open area of each turbulence promoter was also based on the area of the $1\frac{5}{8}$-inch inside-diameter tube.

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RESULTS AND DISCUSSION

Several check runs were conducted in which all operating variables were maintained constant except the water flow to the movable spray. This water flow was so altered that the outlet-gas temperatures varied from 800° to 2000° F and in this range of outlet-gas temperatures the calculated combustion efficiency remained constant. These data indicated that all the water was vaporized before reaching the downstream thermocouple rake.

With all the turbulence promoters investigated, ignition was possible only at inlet-air pressures above 40 pounds per square inch absolute, at inlet-air velocities below 40 feet per second, and at fuel-air ratios above 0.06.

With the conical turbulence promoter, combustion occurred with less noise and pressure fluctuations than with any of the configurations investigated. The stability limits of combustion with this turbulence promoter are shown in figure 4. Inlet-air velocity is plotted against fuel-air ratio for a constant inlet-air static pressure (39.7 lb/sq in. absolute) and two inlet-air temperatures (90° and 225° F). Values of outlet-gas static pressure at the outlet of the water-jacketed tube are indicated beside the data points on figure 4(a). Increases in the inlet-air velocity were accompanied by decreases in the outlet-gas pressures. The outlet-gas pressure was not recorded for all runs. The lean fuel-air ratio limits of combustion were characterized by an abrupt cessation of combustion (blow-out) as the fuel-air ratio was decreased. As the fuel-air ratio was increased to determine the rich limits, the combustion first became unstable and finally blow-out occurred as the fuel-air ratio was further increased. The combustion was characterized by high-frequency vibrations (of the order of magnitude of about 1000 cps). The unstable combustion was characterized also by low-frequency pressure fluctuations and sometimes by sporadic bursts of noisy combustion.

The lean fuel-air ratio limit of combustion did not vary appreciably with inlet-air velocity until the maximum attainable velocity was closely approached. At an inlet-air temperature of 90° F and an inlet-air static pressure of 39.7 pounds per square inch absolute, this lean fuel-air ratio limit was approximately 0.057; at 225° F and 39.7 pounds per square inch absolute, this limit was decreased to about 0.053. At the lower of the two inlet-air temperatures, the maximum inlet-air velocity at which combustion could be maintained was about 64 feet per second and occurred at a fuel-air ratio of 0.065. At the higher inlet-air temperature, the maximum inlet-air velocity was about 83.5 feet per second and occurred at a fuel-air ratio of 0.062.

The curves were not extended to lower inlet-air velocities because combustion was sporadic and intermittently flashed back through the holes in the turbulence promoter when the inlet-air velocity was reduced below approximately 40 feet per second.

The stability limits of combustion with the flat-plate turbulence promoters having 12.4, 17.2, and 21.5 percent open area are shown in figures 5(a), 5(b), and 5(c), respectively. For each percentage of open area, three individual turbulence promoters having 1/8-inch-diameter holes, 1/4-inch-diameter holes, and a single large hole were investigated. A sketch of each turbulence promoter indicating the hole size and arrangement is shown beside each curve in figure 5. The stability limit curves for an inlet-air static pressure of 39.7 pounds per square inch absolute and an inlet-air temperature of 80° F are presented for all turbulence promoters except the one having 21.5 percent open area and 1/4-inch holes (fig. 5(c)); combustion could not be maintained at these conditions with this turbulence promoter. In figures 5(b) and 5(c), additional stability limits are presented for an inlet-air temperature of 200° F.

The curves in figures 5(b) and 5(c) presenting stability limits at the two inlet-air temperatures show trends consistent with those indicated in figure 4; that is, the stability limits were widened and the maximum velocity for stable combustion was shifted to leaner fuel-air ratios as the inlet-air temperature was increased in the range investigated.

For each series of turbulence promoters having a different percentage open area, the intermediate size holes (1/4-in. diameter) gave stable combustion to leaner fuel-air ratios and to higher inlet velocities. As the percentage open area was progressively increased through the range investigated, stable combustion was obtainable to higher inlet-air velocities but there was no appreciable change in the lean fuel-air ratio limits. With turbulence promoters having greater percentage open area, the outlet-gas pressures were higher for a given inlet-air velocity and the data of reference 1 indicate that this increase may account in part for the attainment of higher velocities with these turbulence promoters. Values of maximum velocity for stable combustion (values corresponding to the peaks of the curves in fig. 5) are plotted in figure 6 as a function of hole size in the turbulence promoters.

With none of the flat-plate turbulence promoters investigated was combustion as smooth as with the conical turbulence promoter. With the flat-plate turbulence promoters, slight pressure fluctuations were encountered throughout the operating range and blow-outs were not as abrupt as with the conical turbulence promoter. The conical turbulence promoter had the same number of 1/8-inch holes as the flat-plate turbulence promoter having 1/8-inch holes and 17.2-percent open area. Comparison of the stability limits presented for these two turbulence promoters in figures 4 and 5(b) shows that with the flat-plate turbulence promoter combustion was maintained to a maximum inlet-air velocity of 68 feet per second at an inlet-air temperature of 80° F, whereas combustion was maintained to 64.5 feet per second at an inlet-air temperature of 90° F with the conical turbulence promoter. The lean fuel-air-ratio limits with these two turbulence promoters were nearly the same.

With all the turbulence promoters investigated, the rich fuel-air-ratio limits were not clearly defined because burning became progressively more intermittent as the fuel-air ratio was increased and the rich-limit blow-outs did not occur repeatedly at exactly the same fuel-air ratio. With all the turbulence promoters, burning also became progressively more intermittent and showed a tendency to flash back through the holes in the turbulence promoter as the inlet-air velocity was decreased below approximately 45 feet per second.

With the turbulence promoters investigated, at an inlet-air pressure of 39.7 pounds per square inch absolute and an inlet-air temperature of 80° or 90° F combustion could not be maintained at fuel-air ratios below 0.05 or at velocities above 87 feet per second. With the turbulence promoters investigated at the higher inlet-air temperatures (200° or 225° F) combustion could not be maintained at fuel-air ratios below 0.05 or at velocities above 107 feet per second. These limits are much narrower than the limits of stable combustion encountered with conventional ram jets.

The combustion efficiency ranged between 85 and 95 percent with all the turbulence promoters and operating conditions investigated. No consistent trends were indicated as the inlet-air pressure, inlet-air temperature, inlet-air velocity, and fuel-air ratio were independently varied, possibly because of the narrow ranges investigated.

The enthalpy transferred to the water passing through the cooling jacket amounted to approximately 15 percent of the heating value of the fuel for most runs.

The ratio of the total-pressure loss through the turbulence promoters to the inlet-air velocity pressure $\Delta P/q$ ranged from 100 to 140 at isothermal (no-burning) conditions with the various turbulence promoters. These values of $\Delta P/q$ are 100 to 200 times as great as those obtained with conventional ram jets. The ratio of the total-pressure loss to the velocity pressure based on upstream density and the cross-sectional area of the combustion zone ($1\frac{7}{8}$-in. diameter tube) $\Delta P/q_2$ ranged from 133 to 186 at isothermal conditions. These values of $\Delta P/q_2$ are approximately the same as corresponding values computed for the primary combustion zone of the turbojet combustor of reference 1. The pressure losses through the turbulence promoters investigated were about 10 times as great as those reported in reference 1, indicating that the velocities were much higher in this investigation than in the primary zone of the turbojet combustor. As previously noted, maintenance of stable combustion at low velocities and consequently investigation of the range of velocities existing in the primary zone of the turbojet combustor were impossible.

With burning, the measured values of the pressure drop showed random scatter and averaged 20 percent above the values calculated by adding to the isothermal friction loss the loss corresponding to the measured temperature rise (momentum loss). These results may indicate burning in the boundary layer immediately upstream of the turbulence promoter.

As the movable water spray was positioned progressively closer to each turbulence promoter, in no case was an appreciable change in combustion efficiency noted before reaching the position at which blow-out occurred but the noise changed in tone indicating a change in the resonant frequency. The nominal flame lengths were about 2 inches for the turbulence promoters investigated with blow-out occurring abruptly if the water spray was moved any closer to the turbulence promoter. Because there were no observation windows in the water-jacketed tube, it was impossible to ascertain whether visible flames extended downstream of the water spray or whether the flames changed in appearance as the spray position was changed.

Because combustion started immediately downstream (and perhaps upstream, as previously noted) of the turbulence promoters, they acted as flame holders as well as turbulence promoters. Their effectiveness may be determined by factors other than the turbulence they produced.

SUMMARY OF RESULTS

The results obtained in the investigation of combustion downstream of certain turbulence promoters with premixed vaporized fuel and air in a $1\frac{7}{8}$-inch-diameter water-jacketed tube are summarized as follows:

1. Combustion was maintained at progressively higher inlet-air velocities for a constant inlet-air pressure and temperature as the percentage open area of the turbulence promoters was progressively increased, probably because the pressure in the combustion zone increased with increased open area. For a fixed percentage open area, combustion was maintained at slightly higher inlet-air velocities with the intermediate (1/4 in.) hole size investigated.

2. With the turbulence promoters investigated at an inlet-air pressure of 39.7 pounds per square inch absolute and an inlet-air temperature of 80° to 90° F, combustion could not be maintained at fuel-air ratios below 0.05 or at inlet-air velocities above 87 feet per second. At the higher inlet-air temperatures investigated (200° or 225° F), the limits of combustion were somewhat wider.

3. With all the turbulence promoters investigated, ignition was possible only at inlet-air pressures above 40 pounds per square inch absolute, at inlet-air velocities below 40 feet per second, and at fuel-air ratios above 0.06.

4. The conical turbulence promoter gave burning with less resonance than any of the configurations investigated although it did not permit burning to velocities as high as with a flat-plate turbulence promoter having the same number and size of holes.

5. The combustion efficiency ranged between 85 and 95 percent with all the turbulence promoters and operating conditions investigated.

6. The ratio of the isothermal total-pressure loss through the turbulence promoters to the velocity pressure computed from the upstream density and the cross-sectional area of the combustion zone was approximately the same as the values computed for the primary combustion zone of a typical gas-turbine combustor.

7. Nominal flame lengths of about 2 inches were indicated by use of the movable water spray.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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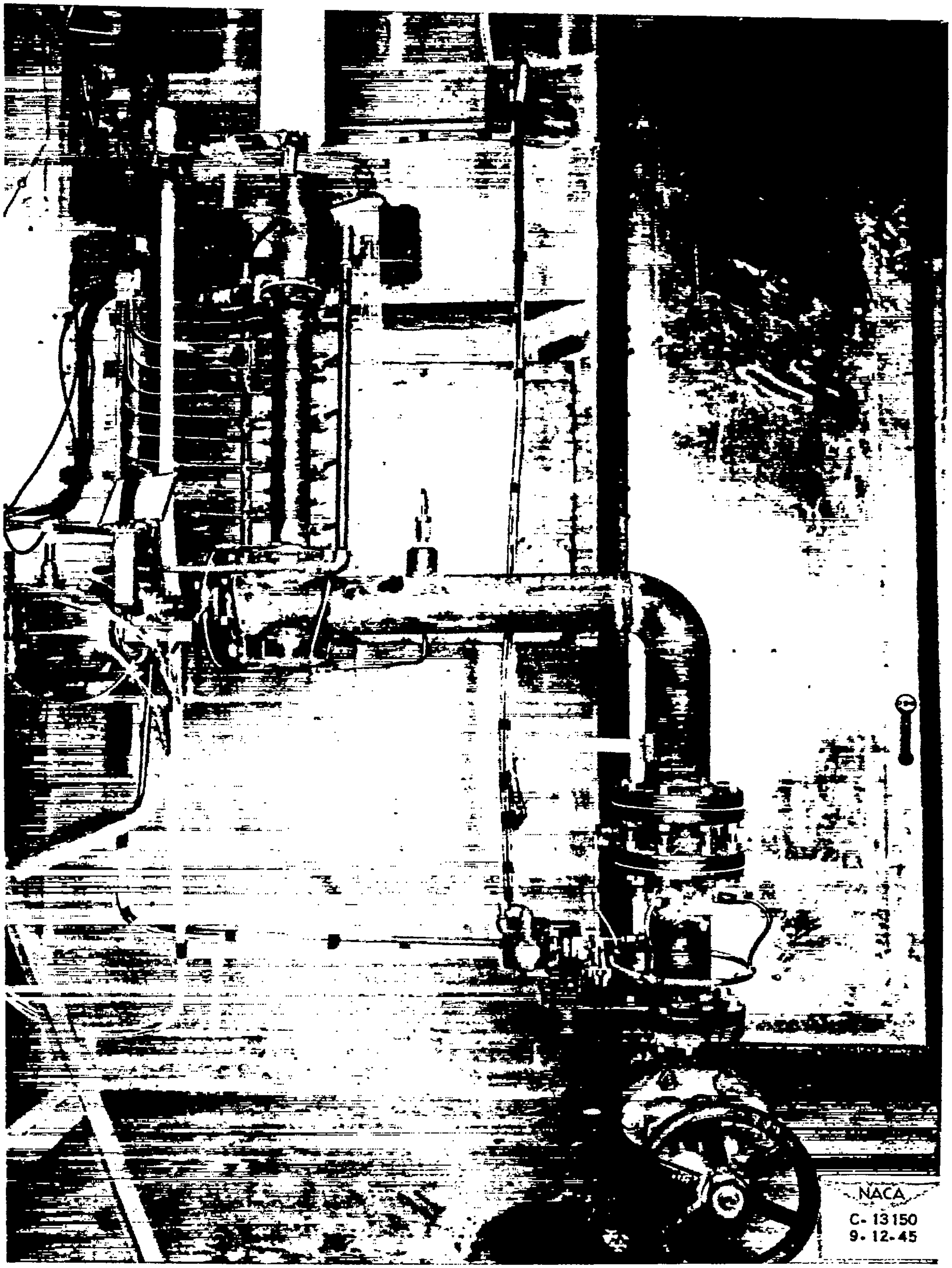

Figure 1. - Photograph of 2-inch combustion apparatus.

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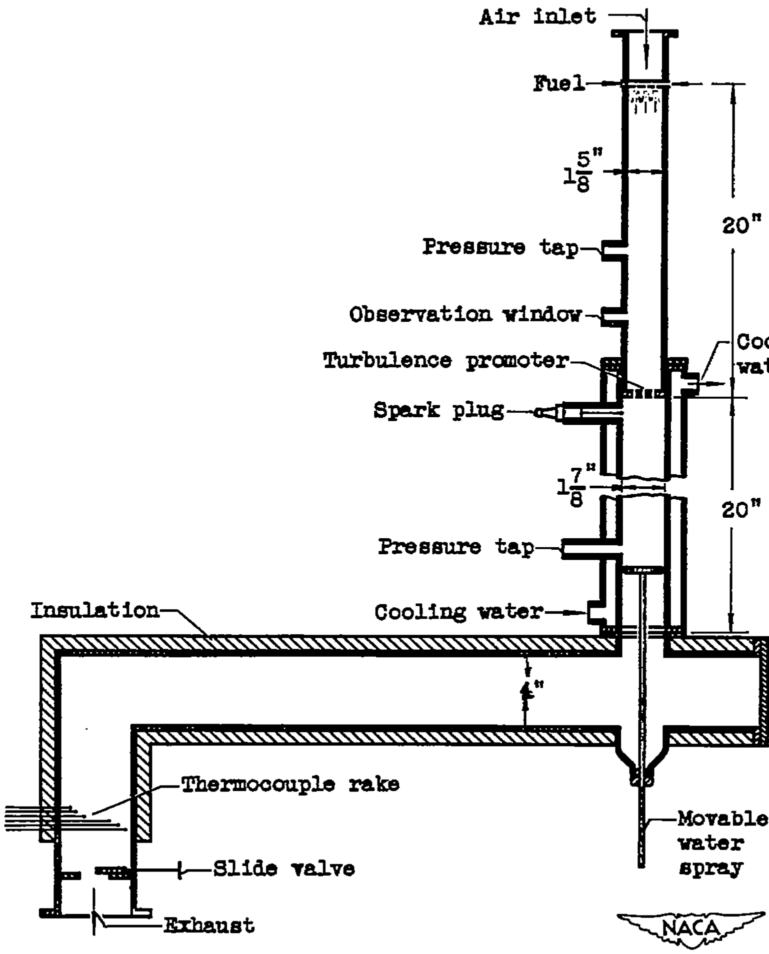


Figure 2. - Diagram of 2-inch combustion apparatus.

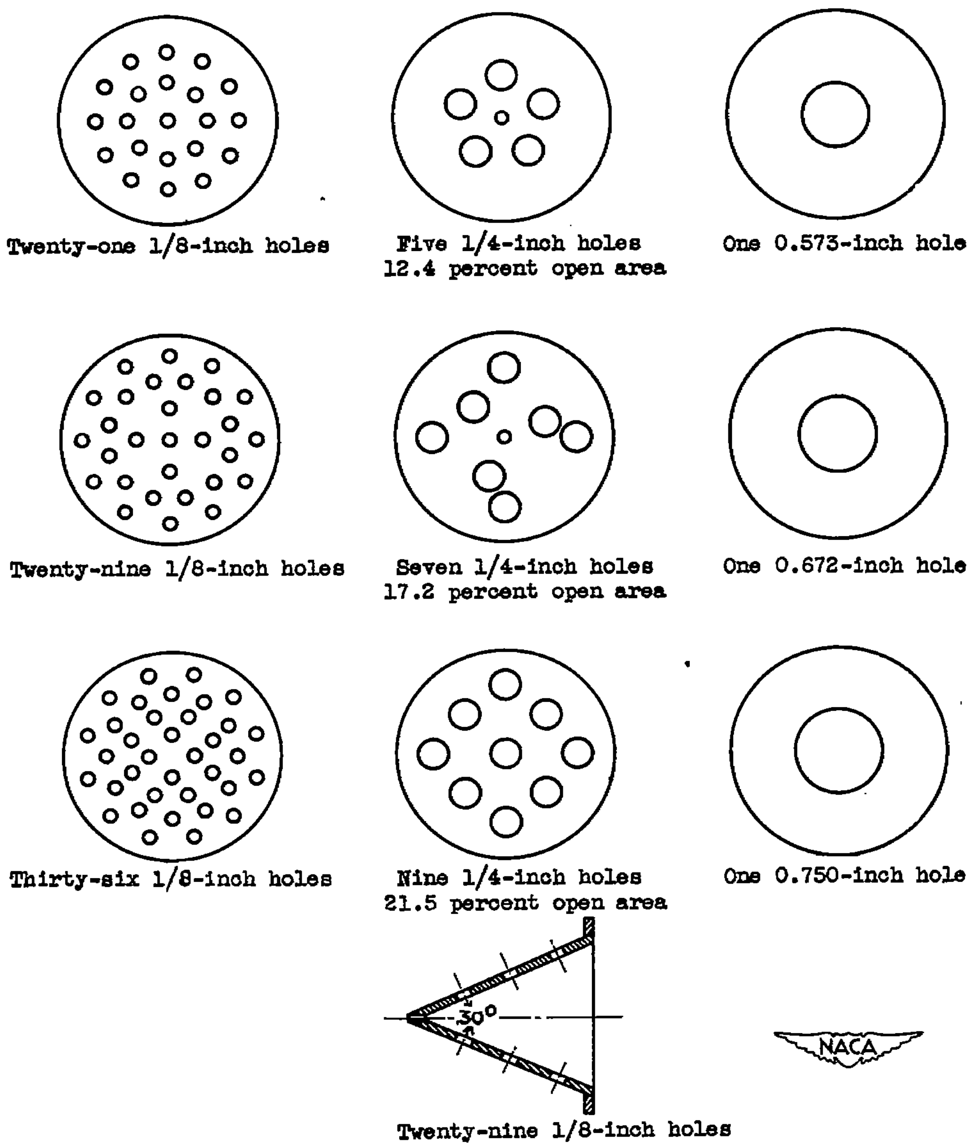
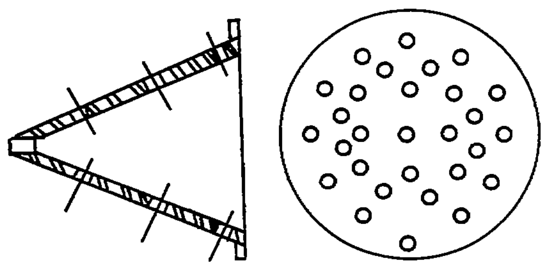
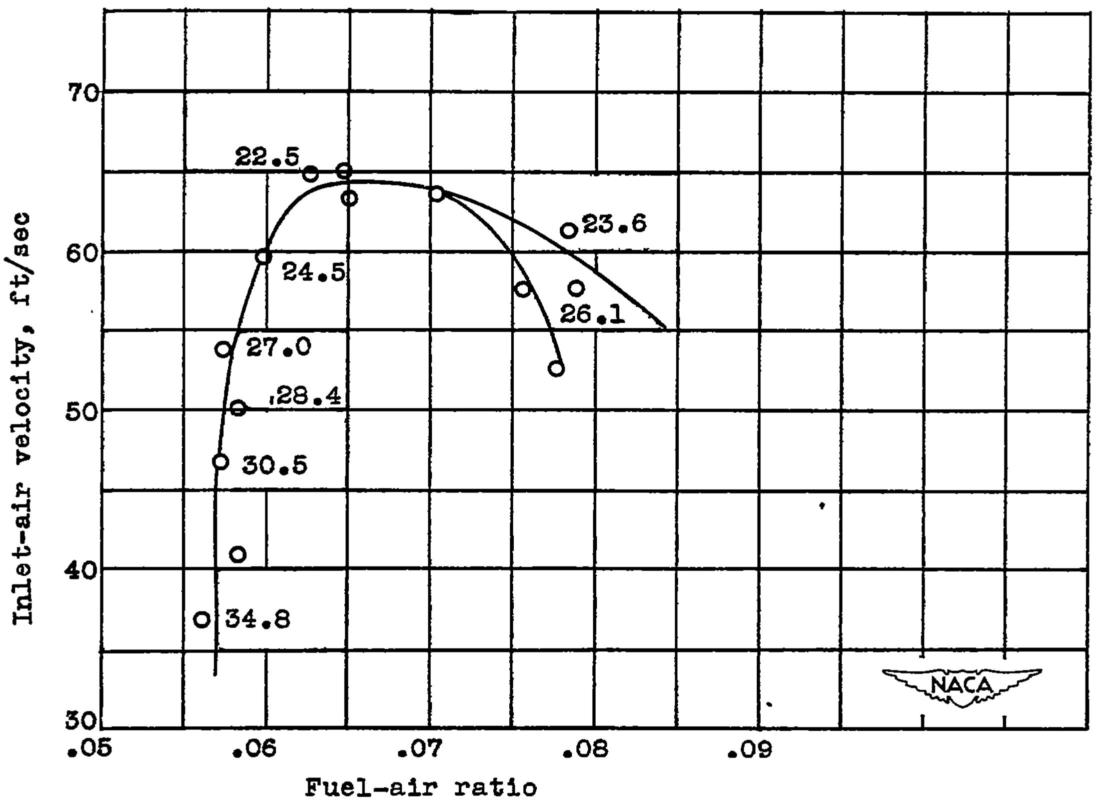


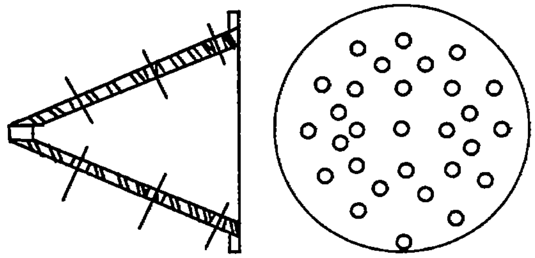
Figure 3. - Turbulence promoters.

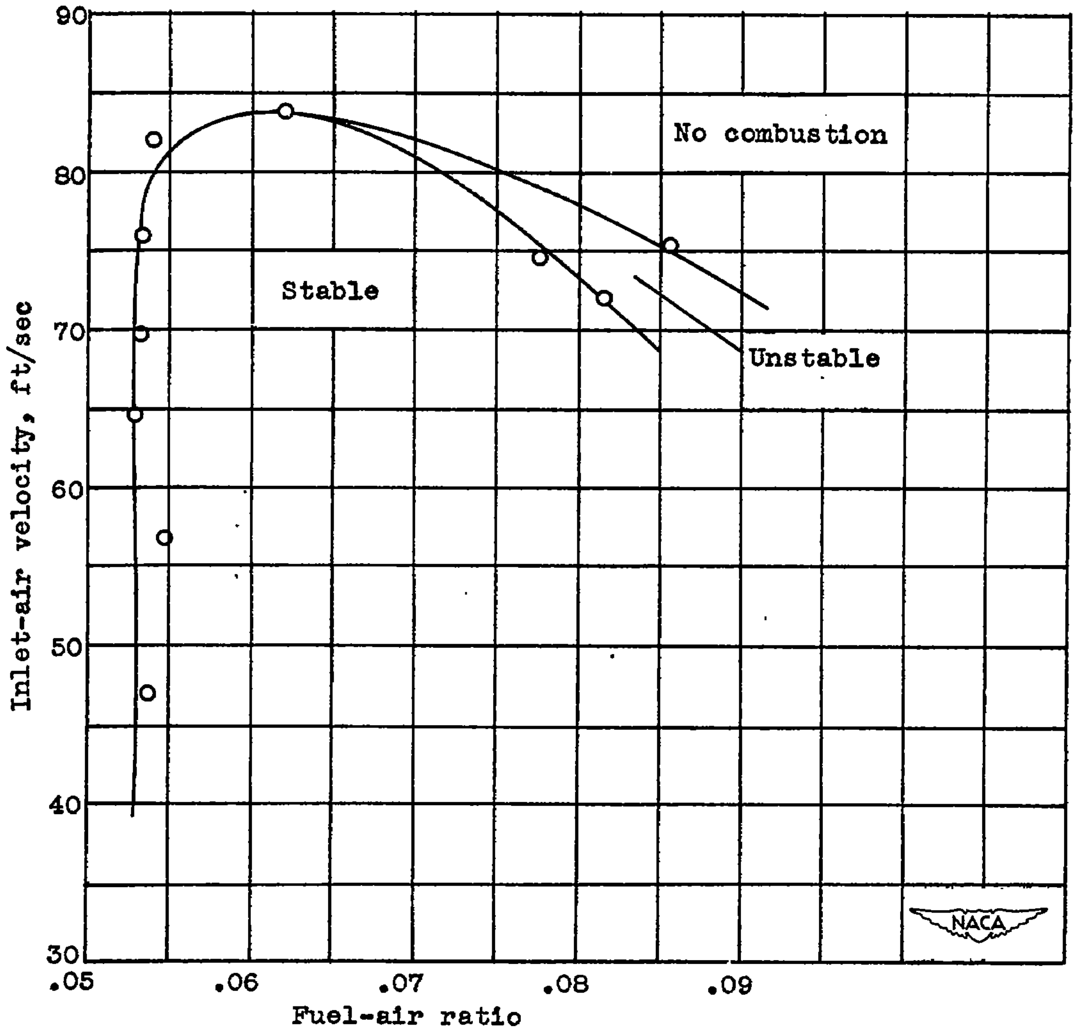




(a) Inlet-air temperature, 90° F. Values of outlet-gas static pressure in pounds per square inch absolute indicated beside data points.

Figure 4. - Effect of inlet-air temperature, inlet-air velocity, and fuel-air ratio on limits of stable combustion of conical turbulence promoter. Inlet-air static pressure, 39.7 pounds per square inch absolute; open-hole area, 17.2 percent.





(b) Inlet-air temperature, 225° F.

Figure 4. - Concluded. Effect of inlet-air temperature, inlet-air velocity, and fuel-air ratio on limits of stable combustion of conical turbulence promoter. Inlet-air static pressure, 39.7 pounds per square inch absolute; open-hole area, 17.2 percent.

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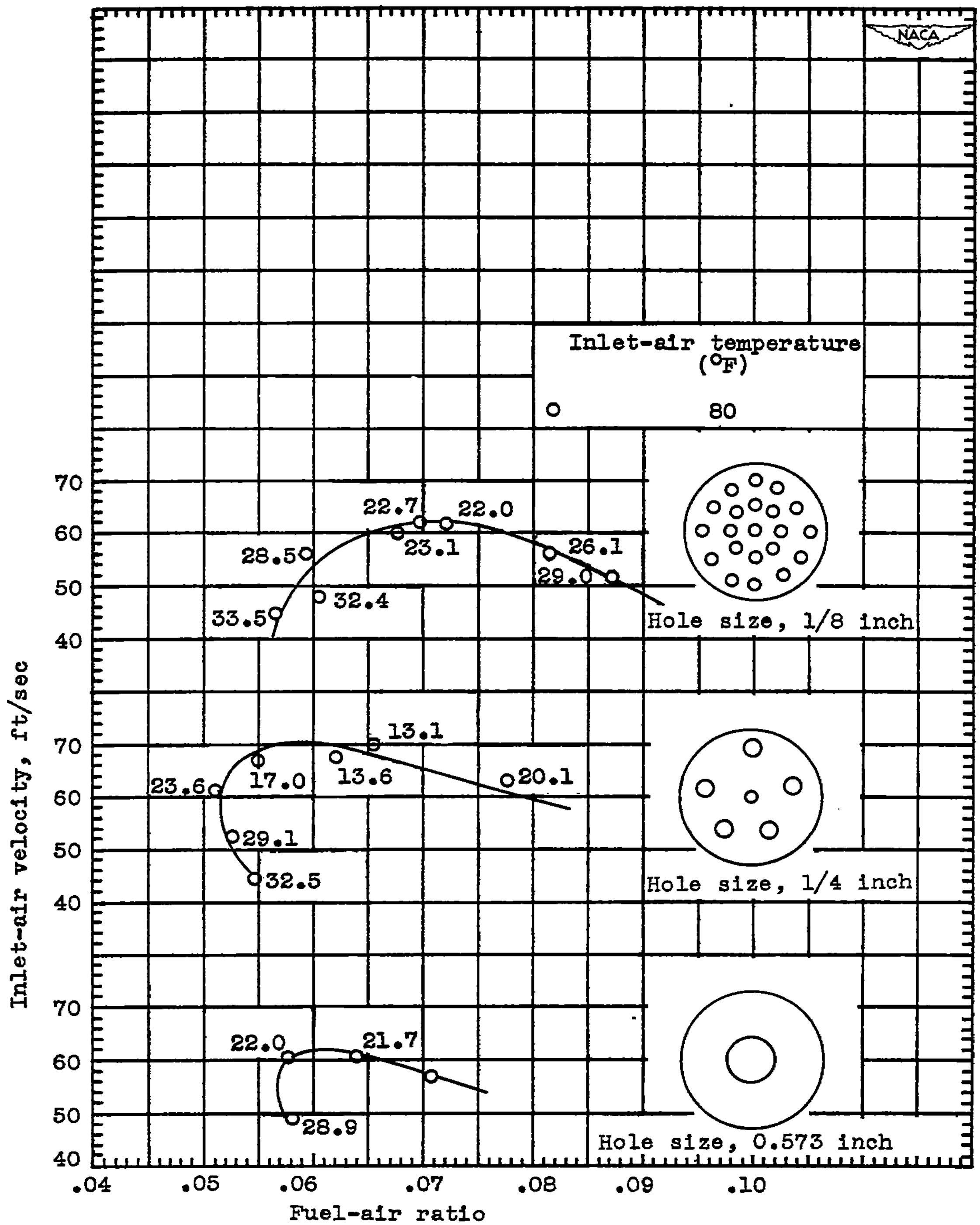
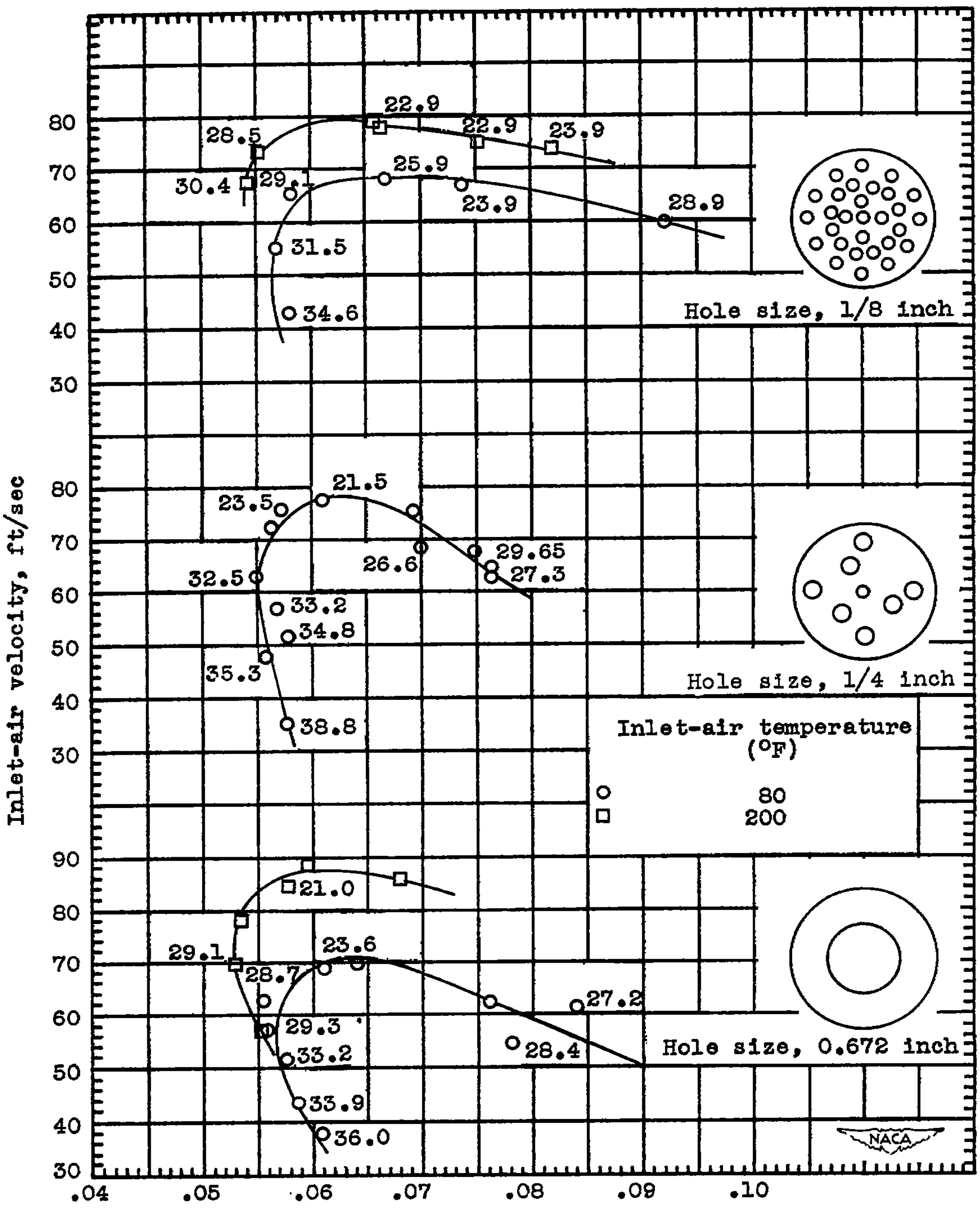


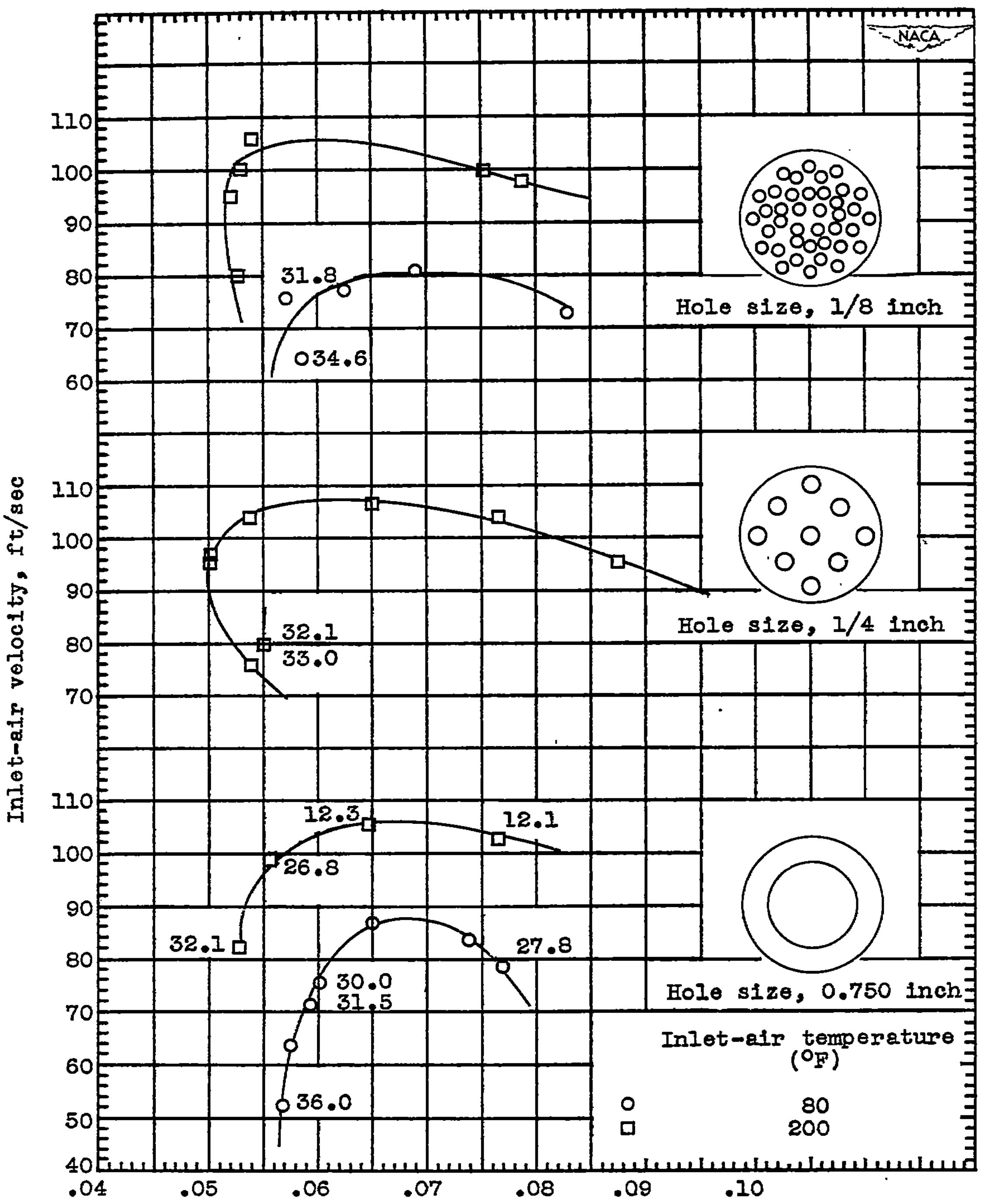
(a) Open area, 12.4 percent.

Figure 5. - Effect of hole size of flat-plate turbulence promoters on limits of stable combustion. Inlet-air static pressure, 39.7 pounds per square inch absolute. Values of outlet-gas pressure in pounds per square inch absolute indicated beside data points.



(b) Open area, 17.2 percent.

Figure 5. - Continued. Effect of hole size of flat-plate turbulence promoters on limits of stable combustion. Inlet-air static pressure, 39.7 pounds per square inch absolute. Values of outlet-gas pressure in pounds per square inch absolute indicated beside data points.



(c) Open area, 21.5 percent.

Figure 5. - Concluded. Effect of hole size of flat-plate turbulence promoters on limits of stable combustion. Inlet-air static pressure, 39.7 pounds per square inch absolute. Values of outlet-gas pressure in pounds per square inch absolute indicated beside data points.

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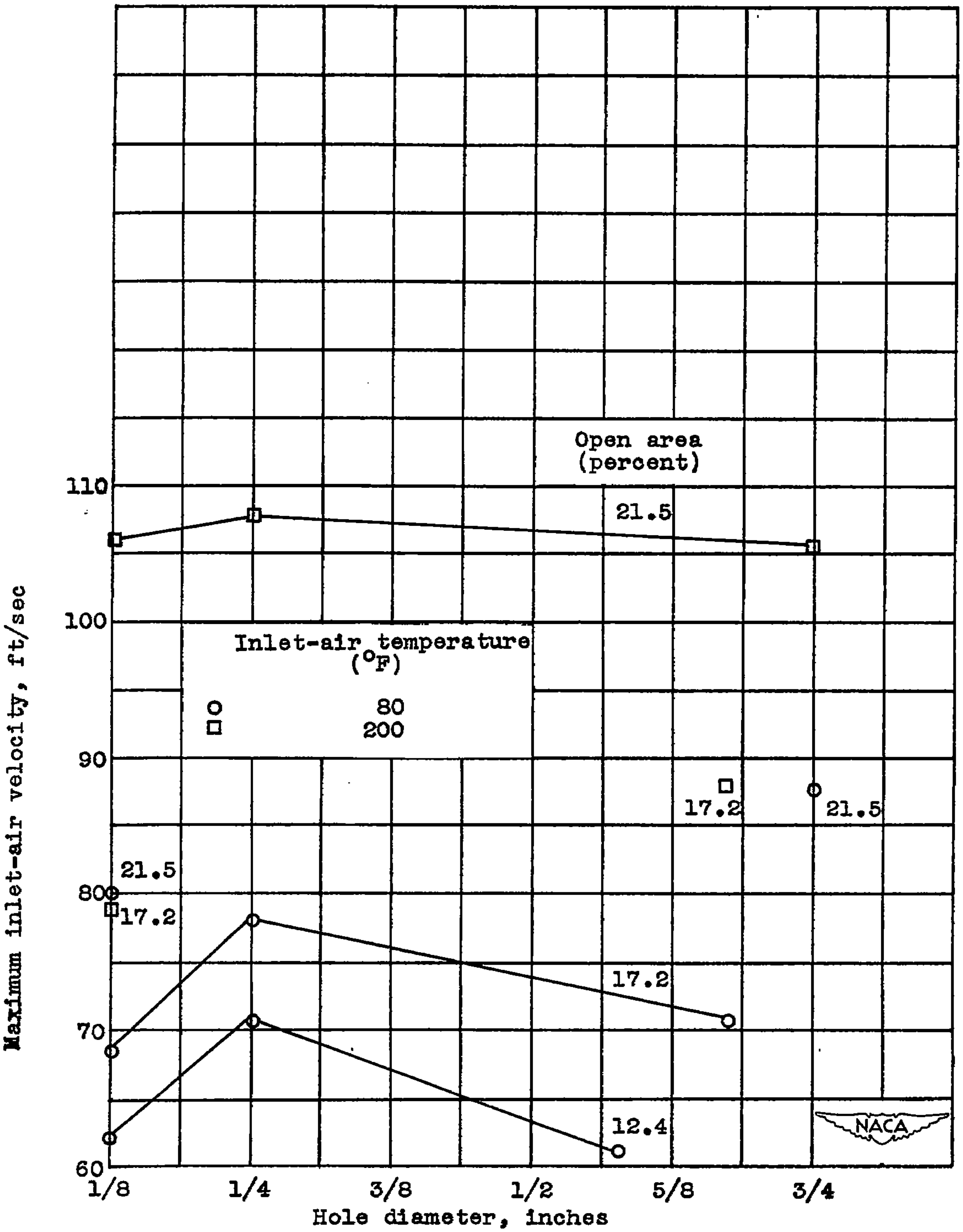

Figure 6. - Effect of turbulence-promoter hole size, open-hole area, and inlet-air temperature on maximum inlet-air velocity at which stable combustion can be maintained. Inlet-air static pressure, 39.7 pounds per square inch absolute.